PV and EV: More than Synergies and 40 Years of Success

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1. Historical Overview

In 1976, the UK inventor Alan T. Freeman (Fig. 1) combined light-weight electric vehicles (EVs) with PV panels and tested their everyday use in the regular traffic[i]. A solar-driven EV built in Australia (Quiet Achiever) demonstrated the possibilities of solar energy by crossing Australia in 1983[ii].

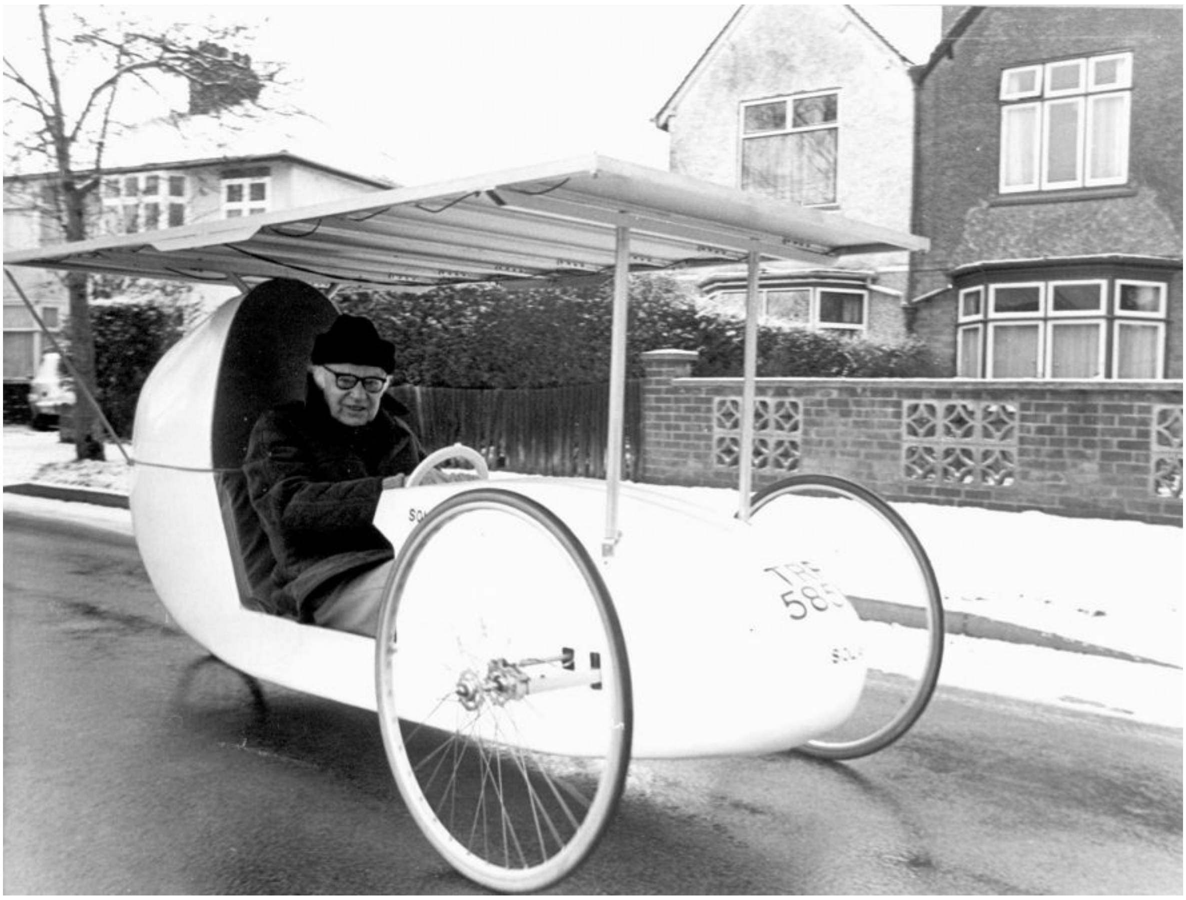

Fig. 1: Mr Alan T. Freeman, retired engineer, 72, owner of the world's first solar powered vehicle, on Rugby street in 1985 (Photo: Rugby Library).

In 1982, the Swiss radio pioneer Matthias Lauterburg (Fig. 2) used a PV-powered Zagato "Zele" for rides in the city of Berne.

The Swiss engineer Gernot Schneider built several solar bicycles with three wheels. The "SOFA III" bicycle was built by the cooperative "Multisolar" in a small series of about 30 vehicles and was a prominent participant in the "Tour de Sol 85". One of the engineers involved in this project was Josef Brusa, the founder of the electric power electronic company Brusa AG.

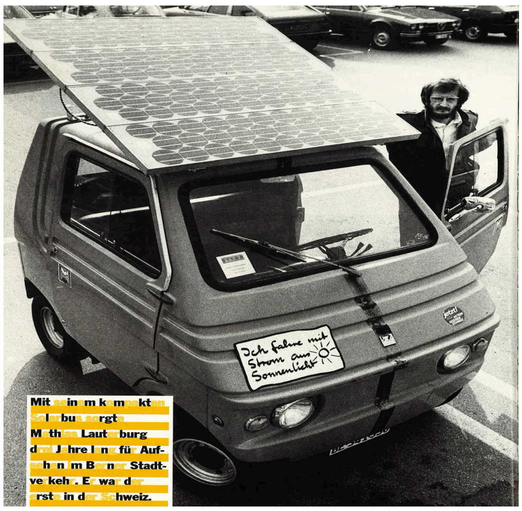

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Fig. 2: Swiss pioneer Matthias Lauterburg riding a "Zele" in the city of Bern in the 1980s. Photo: "Schweizer Illustrierte/ Solarmobile" (Ringier AG).

In 1985, the first solar car race of the world, the Tour de Sol (Fig. 3), was organized in Switzerland with 58 solar cars driving through Switzerland[iii]. Further Tour de Sol races rapidly triggered the construction of cars with light-weight PV panels on their roof, solar gasoline stations (1986) and grid connected PV installations (1986/ 87)[iv].

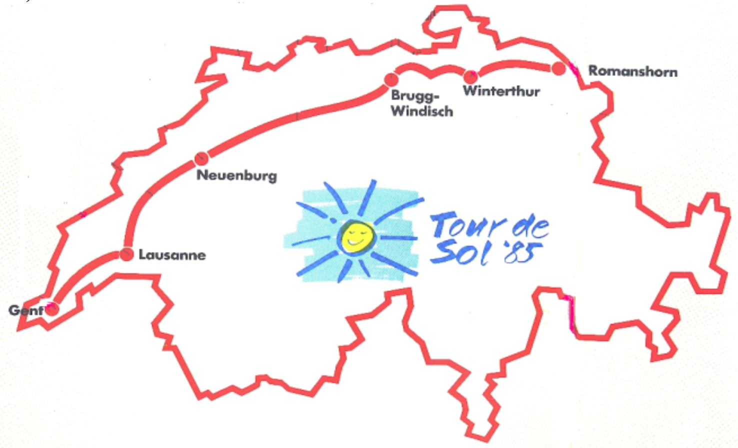

Fig. 3: The Tour de Sol 85 race was originally designed as a PR-tour for the use of solar energy (Tour de Sol/ Muntwyler).

Since then, the combined deployment of PV and EVs has been demonstrated by hundreds of pioneers. With the price drop of grid-connected PV installations and new powerful EVs emerging, this combination of technology is now attractive for everyone. In addition, the current price regime of utility companies with extremely low payments for surplus PV electricity is a new driver for EVs. Today, using an EV is both an attractive possibility to enhance the "own consumption" and to propel the EV with "cheap electricity".

2. PV on EVs

According the technical regulations, the first solar cars on the Tour de Sol 85 all had their solar modules mounted on the car (Fig. 4a-b). The vehicles were so efficient that 480 Wp were sufficient to move them about 80 km each day. With total PV surfaces up to $6m^2$, the solar modules influenced the construction of the whole car[v]. As the PV modules, at that time, lasted longer than 20 years, it was then not the best way to install PV modules.

Fig. 4a: Tour de Sol 1985 entries (Photo: Muntwyler).

Fig. 4b: Tour de Sol 1985 winner «alpha real / Mercedes Benz » (Photo: Muntwyler).

3. Light-weight EVs and PV

The vehicles starting on the "Tour de Sol 85" were light-weight constructions and, consequently, their electricity consumption was in the range of 2-3kWh/ 100 km or below. Some of the vehicles, e.g., the "TWIKE", a highly sophisticated electric 3-wheeler with pedals (Fig. 5), attracted several hundred customers. A similar construction but different design, the Danish "mini-el", even fascinated several thousand customers[vi].

Fig. 5: Roof-top PV installation to drive a so-called “Twike” -see bottom left in Figure (Photo: Muntwyler).

4. From Solar Gasoline Stations to Grid-Connected PV Installations

The technical regulations of the Tour de Sol 1986 permitted the partial placement of the PV modules on so-called mobile “solar gasoline stations[vii]. This allowed the participants to charge the vehicles with a DC-charge, and special trailers were needed to transport the PV panels (Fig. 6).

Fig. 6: New technical regulations on the Tour de Sol 1986 permitted solar gasoline stations, and less PV on the cars was needed (Photo: Muntwyler).

The next "Tour de Sol" innovation were grid-connected PV systems and an AC charge on the Tour de Sol stops (Fig. 7). This concept was less complicated and widely used, and promoted grid connected PV installations. In 1989, the “feed- in tariff” for PV was invented in the Swiss city of Burgdorf, what made Switzerland, in 1990, the market leader of grid-connected PV installations. Today, the feed-in tariff for PV can be very low (4 cents/kWh) in some regions of Switzerland, which makes it very attractive for PV owners to consume the surplus PV electricity on their own by, e.g., charging an EV. Hence, low feed-in tariffs in Switzerland today act like an incentive program for EVs.

Fig. 7: One of the first grid-connected PV installations on the Tour de Sol 1987 at Horlacher AG - providing 3 kWp - enough to move 6 cars (Photo: Horlacher AG).

5. PV on EVs

Thirty years ago, mounting PV on EVs was considered too expensive and ineffective. PV today is, however, cheap and powerful, what makes sense to mount solar panels on entire trucks (such as refrigerated trucks) and cars with a high electric load. In this way, "clean" PV electricity replaces the electric energy produced by the "dirty" combustion engine (Section 7) and acts as a "fuel saver application" (Section 8). This is an important field of research in the IEA Technical Collaboration Program (TCP) "PV and EV" presented by MITI, Japan[viii].

6. The Size of PV Installations for EVs

In the Tour de Sol era, the electric vehicles were considered "light-weight" electric vehicles. The underlying idea was a 2-seater car with lead acid batteries, a range of more than 400 km and a car weight below 600 kg. Detailed safety studies were carried out to ensure the safety of these cars. The studies were funded by the Swiss Federal Office of Energy (SFOE) under a special "Pilot- and Demonstration Program" for "light-weight electric vehicles" 1992-1998. The research was conducted by private industry and research institutes such as the Automotive Engineering Division of the Engineering and Information Technology Department at Bern University of Applied Sciences BFH or by the Swiss Federal Institute of Technology Zürich ETHZ. One of the research outcomes is the "SMART" car (Fig. 8), developed by SWATCH, the Swiss watch producer, and now produced by Mercedes Benz.

Fig. 8: The SMART car is a Tour de Sol outcome.

Fig. 9: PV for one e-bike saves 2000 l gasoline in only 8 years (Photo: Muntwyler).

With the emergence of grid-connected PV installations, there are almost no space limitations any more for solar cells, providing electric energy to propel the heavy and powerful EVs of today. An EV with a consumption of

15kWh/ 100km needs about 2'250 kWh for an annual 15'000 km range, corresponding to a surface of 10-15 m^2 that can be part of a bigger PV installation mounted on a car park, for example. PV installations on car parks were first demonstrated in 1989 in Liestal near Basel (CH)[ix]. E-Bikes need much less PV surface, of course, and less than one square meter is normally sufficient. With the "Flyer" e-bike, model 1996 (Fig. 9), a user commuting 2x10 km a day needs 60 Wp of PV power and saves 2'000 l of gasoline in only 8 years.

7. CO_2 Balance of EVs with PV

A so-called "critical" CO_2 balance of EVs is often mentioned when arguing about the sustainability of EVs. Very often in this context, so-called 'unrealistic' electricity production mixes (e.g., based on brown coal plants) are then used when presenting this "critical" CO_2 balance of EVs. Here, we provide evidence that, in most cases, EVs tend to improve the CO_2 balance. Table 1 demonstrates that technology mix of PV (and wind) and EV is especially favorable[x], as it combines the efficiency of the electric motor with a highly efficient, low CO_2 electricity production. The CO_2 balance even improves when the electricity in the grid is characterised by a high share of electricity produced from renewables (wind-, hydro plants and other minor producer with low CO_2 emissions). An electricity mix with bio fuels etc. is much less favorable as the efficiency of the electricity production is magnitudes below PV.

Table 1: CO_2 balance of EVs running with PV (calculation by Muntwyler).

Model	**CO_2-emissions**	**TWIKE**	**BMW i3**	**Renault ZOE**	**Opel Ampera**	**Tesla**	**Renault Clio 1.2**	**BMW X5 3l**
Electricity consumption for driving 100 km [kWh]		5	12	14	15	20	gasoline	gasoline
Energy source	[kg/ kWh]	[gr/ km]	[gr/ km]	[gr/km]	[gr/km]	[gr/ km]	[gr/km]	[gr/km]
Brown coal (lignite)	1.23	61.5	147.6	172.2	184.5	246		
Stone coal (anthracite)	1.08	54	129.6	151.2	162	216		
Gas	0.64	32	76.8	89.6	96	128		
PV	**0.03**	**1.5**	**3.6**	**4.2**	**4.5**	**6**		
Wind	0.01	0.5	1.2	1.4	1.5	2		
CO_2 EU-mix (only emissions)	0.46	23	55.2	64.4	69	92		
CO_2 (GE-mix)	0.48	24	57.6	67.2	72	96		
CO_2 EU- LCA mix (with plant etc.)	0.578	28.9	69.36	80.92	86.7	115.6		
CO_2 CH-mix certified (Frischknecht 2012)	0.014	0.7	1.68	1.96	2.1	2.8		
Petrol/gasoline	---	0	0	0	0	0	**137**	**197**

Legal obligation for EU fleets in terms of CO_2-emissions: 95 gr/ km from 2020 onwards!

Unfortunately, some oil companies or researchers interested in funding to continue focusing their research on technology other than PV may view the results in Table 1 as "disturbing". Policy makers also often prefer solutions that postpone important decisions or solutions not in favor of renewable energies[xi]. The "feed-in tariff" in Switzerland, for example, has, unfortunately, been cut-off by political measures in recent years (Pronovo AG). Based on these political developments, a surplus PV electricity fed into the grid today is now offered a ridiculously low return on investment. Trapped by these changes in the law, small producers of photovoltaic electricity in Switzerland are today no longer encouraged to sell their own electricity produced from PV on the free market. Rather, they are likely to consume their surplus PV electricity on their own. In this context, additional electricity consumers, such as EVs, offer an interesting possibility and can motivate PV producers to increasingly purchase an EV instead of a car with a conventional combustion engine.

In conclusion, the combination of PV and EV technology becomes a convincing business model in view of the CO_2-balance. Complemented with regionally different shares of wind- or hydro-electricity, PV and EV is superior to all other technology and a winner in the future (Fig. 10).

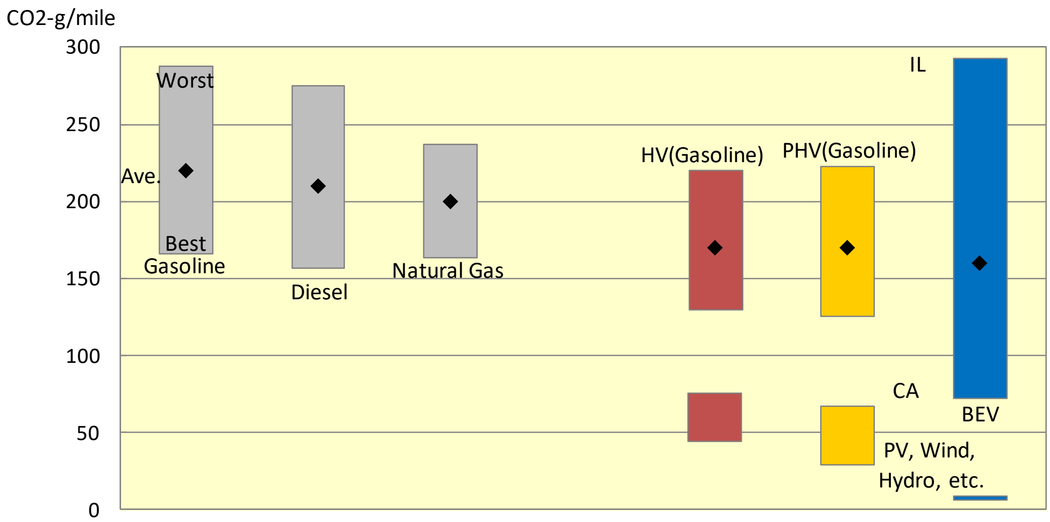

Fig. 10: Well-to-wheels greenhouse gas emissions in 2035 for a mid-size car. Source: U.S. Department of the Environment, Offices of Bioenergy Technologies, Fuel Cell Technologies & Vehicle Technologies, 10 May 2013.

8. Costs of PV and EV

While the combination of an efficient electric motor and low CO_2-emission PV electricity offers dramatic comparative ecological advantages over combustion engines (Section 7), the economic added value is also considerable. As illustrated below, the added value is even more significant when the PV surface generating this electricity is part of a larger PV installation (see also Fig. 11).

Fig. 11: A plug-in hybrid Opel "Ampera" car is being charged in the solar car park in front of the Photovoltaic Laboratory at Bern University of Applied Sciences BFH in Burgdorf, Switzerland (photo: PV LAB BFH-TI).

Example: A typical middle-class gasoline car realistically consumes about 9 l / 100 km with the cost for gasoline being CHF 1.6 / l. If one drives 1500 km, the resulting costs for such a car are CHF 64'800 (assuming the same gasoline costs in the next 30 years as today). Additional costs for service, oil, higher insurance costs, etc. are not included yet. As a comparison, a typical plug-in hybrid car such as the Opel "Ampera" (Fig. 11), or an EV with a range extender, consumes ca. 15 kWh/ 100 km. If one drives 15'000 km, a PV installation in the order of about 2'500 Wp is needed to produce 2'500 kWh/ year. To gain this amount of electricity production, a PV surface of 12-20 m^2 should be installed. When this surface size is part of a larger PV installation (e.g., car park) it will cost about sFr. 5'000. - which is equal to the costs for gasoline for 30 years. The above comparison demonstrates that EVs also offer a dramatic economic advantage over conventional gasoline cars, which event increases when PV is part of a larger PV installation.

9. PV on Ships

PV can also be installed on mobile surfaces such as ships as was first demonstrated in 1978 by Alan Freeman[xii]. First competitions of solar-powered boats were organized during the Tour de Sol 1988 (Fig. 12) on the Swiss lake of Neuchâtel in Estavayer-le-Lac[xiii]. Since then, solar-powered ships have mainly been constructed for demonstration and recreational applications (Fig. 13). The fist solar-powered boat crossing the Atlantic (in 2017) was the Swiss "Sun21" solar boat. The Swiss "Tûranor PlanetSolar" solar boat (Fig. 14) even became famous for its trip around the world in 2010/ 2011. New developments include electric ferries in the Nordic countries that are charged on the ports. Important outcomes are also expected from Task 38 "Maritime applications (E-ships)" in the Technical Collaboration Program (TCP) "Hybrid- and Electric Vehicles" (HEVs) of the International Energy Agency (www.ieahev.org).

Fig. 12: First winner of the solar boat race during the Tour de Sol 1988 (Fachhochschule Konstanz, Germany, with Prof. Dr. Christian Schaffrin). Photo: FH Konstanz

Fig. 13: Solar catamaran offering commercial boat trips (lake of Biel, Switzerland). Photo: Wikipedia

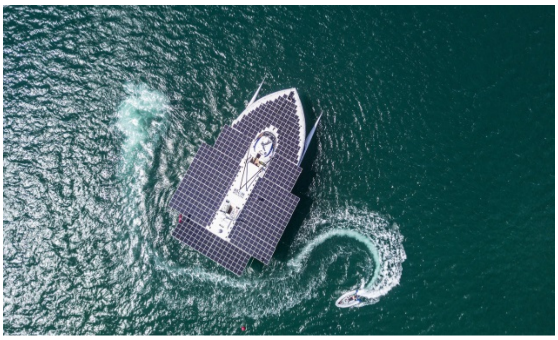

Fig. 14: Tûranor PlanetSolar solar boat. Photo: Wikip.

10. PV on Planes

PV powered planes have been known since the flight of the "Gossamer Penguin" of Paul McCready in 1979 (Fig. 15) that also crossed, in 1981, the Channel with the PV-powered "Solar Challenger"[xiv]. Since then, many solar powered planes have been constructed, the most spectacular being the "Solar Impulse II" (Fig. 16) of the Swiss pioneer team "Piccard/ Boschberg"[xv]. The practical installation and use of PV on the wings is technically very critical as planes bend their wings during the flight and, in addition, last very long.

Fig. 15: Gossamer Penguin (left) and Solar Challenger (right)

Fig. 16: Solar Impulse II flies around the world 1997). Photo: Solar Impulse

Fig. 17: Icaré glider, University Stuttgart (1998). Photo: Uni Stuttgart

Like the installation of PV modules on carports, the placement of solar panels on the roofs of hangars or big airport buildings is interesting. Yet, airport hangars are often oriented towards the south and their roofs incline towards the north. Consequently, they need redesigning to become more suitable for the installation of PV modules. The surplus electricity that is not used to charge the electric planes can, as on solar car parks, be fed into the grid.

11. Task "PV and Transportation" in the IEA Technical Collaboration Program (TCP) "Photovoltaics"

To foster the combined development of "EVs and PV", the Technical Collaboration Program (TCP) "Photovoltaics" started a Task "PV and transportation" (Fig. 18). Four Sub-Tasks are planned, being:

- Subtask 1: Benefits and requirements for PV-powered vehicles
- Subtask 2: PV-powered applications for electric systems and infrastructures
- Subtask 3: Potential contribution of PV in transport
- Subtask 4: Dissemination

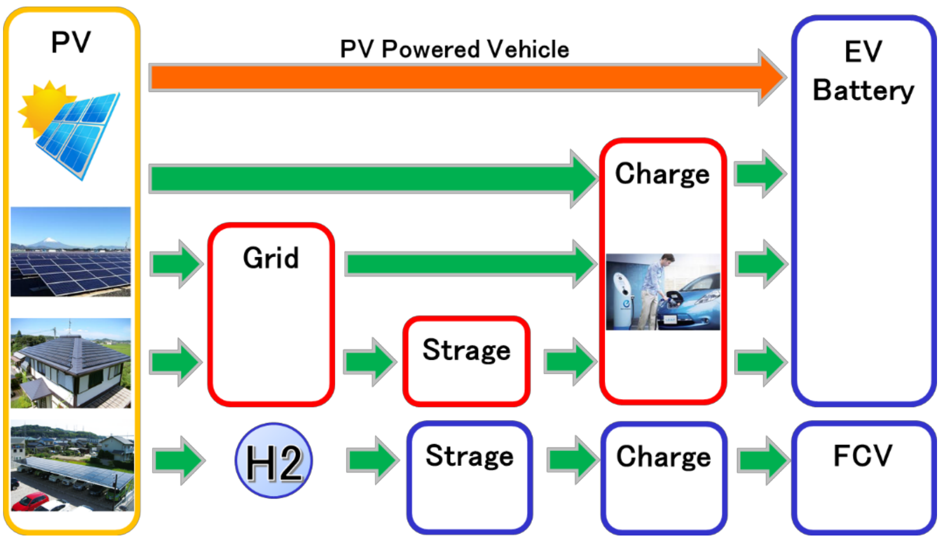

Fig. 18: Schematics of the Task "PV for Transport" in the IEA TCP "Photovoltaics".[xvi]

The launching workshop will be organized by the Photovoltaic Laboratory (PV LAB) at Bern University of Applied Sciences BFH in Burgdorf, Switzerland on 12 October 2018. Researchers interested in participating are invited to contact the author. In October 2018, final decisions will also be taken by the TCP "Hybrid- and Electric Vehicles" (HEVs) onto whether or not to join the Task "PV for Transport" in the TCP "Photovoltaics"[xvii].

12. Outlook: The World is Electric and EVs run with PV Electricity

It has been demonstrated that the combination of PV + EV technology is a highly efficient renewable energy system that can not only replace dirty old technology (combustion engine), but also eliminates a contaminator that is harmful for both humans and the environment. It has also been illustrated that new markets are offered in the future for all possible combinations of PV + EV technology. The implementation of this smart ecological and economic solution to environmental pollution and political dependency is easy, both at country level and globally.

In Switzerland, for example, there are about 5 million cars (ca. 600 cars/ 1'000 inhabitants). With a consumption of 12 kWh/ 100 km (BMW i3) and 12'000 km per year, about 1'500 Wp per car are needed, hence an additional installed PV power of about 8 GWp. This is in addition to the 12 GWp aimed at in the "Swiss Energy Strategy 2050" of the Swiss Government up to 2050[xviii]. The total of 20 GWp is an improvement of 67% of the 12 GWp goal and seasonal fluctuations in PV electricity can be balanced by hydro storage. As some production goals in the "Swiss Energy Strategy 2050" are not realistic (e.g., 4TWh from geothermal), it is expected that PV will produce about 24 TWh per year in 2050. This is a 3 kWp PV installation per every individual Swiss inhabitant, i.e., a PV surface 15-20 m^2 only, which is about 12 times the PV power actually installed in Switzerland. This PV production goal can be reached by 2050.

Globally, there are more than 1 billion cars. If all cars are replaced by EVs and moved by PV electricity, the total PV power needed is around 1'500 GWp, i.e., a surface of 10'000 km^2 and 3-times more PV power than currently installed in the world. As in the case of Switzerland, a time frame of 20-30 years is realistic to achieving this PV production goal.

Acknowledgements

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References

[i]Solar energy for motive power, A.T. Freeman, self-published, Warwickshire England, 1983
[ii] Solarmobile, Christa Dettwiler/ Urs Muntwyler, page 84-85. Ringier Verlag 1985
[iii] Solarmobile, Christa Dettwiler/ Urs Muntwyler, page 49-63, Ringier Verlag 1985
[iv] Energie für Elektroautos, Hrsg. Konstantin Ledjeff, page 70ff., Urs Muntwyler, C.F. Müller Karlsruhe 1993
[v] Technical regulations Tour de Sol 85, Urs Muntwyler, S.7; Tagungsband „Solarmobile – Bau und Konstruktion", Verlag Sonnenenergie, Schweizerische Vereinigung für Sonnenenergie, SSES, 1985
[vi] Energie für Elektroautos, Hrsg. Konstantin Ledjeff, page 70ff., Urs Muntwyler, C.F. Müller Karlsruhe 1993
[vii] Tagungsband "Solarmobile im Alltag" page 191, Hrsg. Urs Muntwyler, SSES/ Tour de Sol, 1987
[viii] Working plan Task 17 IEA TCP PVPS, „PV + Transport", version 3.3.3., Aprile 2018, Professor Toshio Hirota, Waseda University
[ix] Energie für Elektroautos, Hrsg. Konstantin Ledjeff, page 94, Urs Muntwyler, Verlag C.F. Müller Karlsruhe 1993
[x] Electric vehicles powered with PV electricity as new driver for photovoltaics, Urs Muntwyler/ Eva Schüpbach, EUPVSEC 2016
[xi] Political discussions around the people vote for the "energy strategy 2050" in Switzerland 2017
[xii] Solar energy for motive power, A.T. Freeman, self-published, Warwickshire England, 1983
[xiii] Solarbootrennen an der Tour de Sol 1988, Barbara Kruspan, page 231ff, Tagungsband „Solarmobile im Alltag. Tour de Sol, 1989
[xiv] Potential of E-Flight 2014;Urs Muntwyler, Andrea Vezzini | KINTEX, Korea, May 2015
[xv] Mit der Sonne um die Welt, Bertrand Piccard/ André Borschberg, Malik, 2017
[xvi] Workplan „PV and Transport", draft workplan 2018-2020; version 2.0.2.; 8. Nov. 2018, Prof. Toshio Hirota
[xviixvii] PV for Transport, Draft Task Workplan for 2018-2020, Professor Toshio Hirota, Waseda University, 2017
[xviii] PV as a main source of electricity in the „Energy - Challenge in Switzerland", Urs Muntwyler, EUPVSEC 2015